Dissipation and memory domains in the quantum model of brain

Eleonora Alfinito and Giuseppe Vitiello
Dipartimento di Fisica, Università di Salerno, 84100 Salerno, Italy
INFM Sezione di Salerno and INFN Gruppo Collegato di Salerno
alfinito@sa.infn.it
vitiello@sa.infn.it

Abstract

We shortly review the dissipative quantum model of brain and its parametric extension.

1 Introduction

Statistical mechanics predicts macroscopic laws exhibiting ordering and regularities in the behavior of systems made by a large number of components. Schrödinger, however, points out that such "regularities only in the average" of statistical origin are not enough to explain the high stability and the high degree of ordering of living matter. Pretending to explain the biological stability in terms of the regularities of statistical origin would be the "classical physicist's expectation", that "far from being trivial, is wrong" [1]. Schrödinger makes the distinction between ordering generated by the "statistical mechanisms" and ordering generated by "dynamical" quantum (necessarily quantum!) interactions among the atoms and the molecules. Such a distinction between the "two ways of producing orderliness" is of crucial relevance in the study of living matter and of brain. In such a line of thought has to be framed the quantum model of brain originally proposed by Ricciardi and Umezawa in 1967 [2] and further developed by Stuart, Takahashi and Umezawa [3, 4] (see also [5]). To a similar framework also belongs the dynamical model for living matter based on the boson condensation mechanism, proposed by H. Fröhlich [6] in the middle of the 1960s. The Fröhlich model was further developed in the 1980s thus leading to the quantum field theory (QFT) approach to living matter [7, 8].

In the 1960s, the theory of the dynamical generation of macroscopic ordered states in many body physics was developed and experimentally tested in the observations on superconductors, ferromagnets, superfluids, crystals. Such a theory is based on the key mechanism of the spontaneous breakdown of symmetry in QFT by which long range correlations (the Nambu-Goldstone (NG) boson modes) are dynamically generated [9, 10]. On the other hand, it was already experimentally well established, since Lashley's and Pribram's [11, 12] pioneering work, that many functional activities of the brain involve extended assembly of neurons. On this basis, Pribram introduced concepts of Quantum Optics, such as holography, in brain modeling [11]. In the brain, information is indeed observed to be spatially uniform. While the activity of the single neuron is experimentally observed in form of discrete and stochastic pulse trains and point processes, the "macroscopic" activity of large assembly of neurons appears to be spatially coherent and highly structured in phase and amplitude [13, 14]. The quantum model of brain is firmly founded on such an experimental evidence. The model is in fact primarily aimed to the description of non-locality of brain functions, especially of memory storing and recalling. The mathematical formalism in which the model is formulated is the one of QFT. The motivation for using such a formalism is explained by Umezawa in one of his last papers [15]: "In any material in condensed matter physics any particular information is carried by certain ordered pattern maintained by certain long range correlation mediated by massless quanta.

It looked to me that this is the only way to memorize some information; memory is a printed pattern of order supported by long range correlations...If I could know what kind of correlation, I would be able to write down the Hamiltonian, bringing the brain science to the level of condensed matter physics." In the model the "dynamical variables" are not the neurons and the other cells (Stuart, Takahashi and Umezawa have observed [3], with a pleasant sense of humor, that "it is difficult to consider neurons as quantum objects"), but they are identified [16] with those of the electrical dipole vibrational field of the water molecules [8] and of other biomolecules present in the brain structures, and with the ones of the associated NG modes, named the dipole wave quanta (dwq) [17]. The model exhibits interesting features related with the rôle of microtubules in the brain activity [11, 12, 18] and its extension to dissipative dynamics [17] allows a huge memory capacity. The dissipative quantum model has been investigated [19] also in relation with the modeling of neural networks exhibiting long range correlation among the net units. The parametric extension of the model has been also considered [20].

In the following we briefly review some aspects of the dissipative parametric quantum model. For sake of shortness we omit mathematical details. These are reported in the quoted literature.

2 The quantum model of brain and dissipation

In QFT spontaneous breakdown of symmetry occurs when the dynamical equations are invariant under some group, say G, of continuous transformations, but the minimum energy state (the ground state or vacuum) of the system is not invariant under the full group G. In such a case the vacuum is an ordered state and massless particles (the NG bosons), also called collective modes, are dynamically generated and acting as *long range correlations* [9, 10]. Propagating over the whole system, they are the carriers of the ordering information: *order manifests itself as a global property which is dynamically generated*. For example, the magnetic order in ferromagnets is a diffused, i.e. macroscopic, feature of the system. In this way in QFT it is possible to describe "macroscopic quantum systems".

Since the collective mode is a massless particle, its presence (*condensation*) in the vacuum does not add energy to it: the stability of the ordering is thus insured. As a further consequence, infinitely many vacua with different degrees of order may exist, corresponding to different densities of the condensate. In the infinite volume limit they are each other physically (unitarily) inequivalent and thus they represent possible physical phases of the system. The actual phase in which the system sits is determined by some external agent, acting as a trigger of the symmetry breakdown. The

observable specifying the ordered state, called order parameter, acts as a macroscopic variable since the collective modes manifest a *coherent* dynamical behavior. The order parameter is specific of the kind of symmetry into play and its value may be considered as a *code* specifying the vacuum.

The conclusion is that stable long range correlation and diffuse, nonlocal properties related with a code specifying the system state are dynamical features of *quantum* origin.

We remark that the von Neumann theorem in quantum mechanics (QM) states that all the representations of the canonical commutation relations are unitary (and therefore physically) equivalent in systems with a finite number of degrees of freedom. In QFT, where the number of degrees of freedom is infinite, the von Neumann theorem does not hold and infinitely many unitarily inequivalent representations exist. It is because of the existence of such inequivalent representations that dynamically generated ordering may exist in a stable state in QFT.

In the quantum model of brain [2] memory recording is represented by the ordering induced in the ground state by the condensation of NG modes dynamically generated through the breakdown of the rotational symmetry of the electrical dipoles of the water molecules. They are the dipole wave quanta (dwq). The trigger of the symmetry breakdown is the external informational input. The "code" classifying the recorded information is identified with the "order parameter". The recall mechanism is described as the excitation of dwq from the ground state under the action of an external imput similar to the one which has previously produced the memory recording.

The high stability of memory demands that the long range correlation modes (the dwq) must be in the lowest energy state (the ground state), which also guarantees that memory is easily created and readily excited in the recall process. The long range correlation must also be quite robust in order to survive against the constant state of electrochemical excitation of the brain and the continual response to external stimulation. It can be shown [8] that the time scale associated with the coherent interaction in the QFT of electrical dipole fields for water molecules is of the order of 10^{-14} *sec*, thus much shorter than times associated with short range interactions, and therefore these effects are well protected against thermal fluctuations. At the same time, the brain electrochemical activity must be coupled to the correlation modes. It is indeed the electrochemical activity observed by neurophysiology that provides a first response to external stimuli. The brain is then modeled [3, 4] as a "mixed" system involving two separate but interacting levels. The memory level is a (macroscopic) quantum dynamical level, the electrochemical activity is at a classical level.

Note that vacua labeled by different code numbers are accessible only through a sequence of phase transitions form one to another one of them. This process destroys previously stored information (*overprinting*). This problem of *memory capacity* arises because in the model there is only one kind

of code number since only one kind of symmetry is assumed (the dipole rotational symmetry). In order to avoid overprinting a huge number of symmetries (a huge number of codes) [3] could be assumed. This would introduce serious difficulties and spoil the model practical use.

However, the memory capacity can be enormously enlarged [17] by considering the intrinsic dissipative character of the brain dynamics (the brain is an *open system* continuously coupled to the environment). In fact, let us denote the dwq variables by A_k and recall that the canonical formalism for dissipative systems [21, 17] requires the introduction of a "mirror" set of dynamical variables, say $\tilde{A}_k$, describing the environment. The number $\mathcal{N}_A$ for all k of A_k-modes, condensed in the vacuum $|0>_{\mathcal{N}}$, constitutes the "code" of the information. The crucial point of dissipative dynamics is that the vacuum state is now defined to be the state in which the *difference* $\mathcal{N}_A - \mathcal{N}_{\tilde{A}}$ for all k is zero. Thus we see that there are infinitely many vacua, each one corresponding to a different value of the code $\mathcal{N}_A$. Moreover, each of these states is unitarily inequivalent to the other ones, and thus "protected" from unwanted interferences with other memory states. The "brain (ground) state" is then represented as the collection (or the superposition) of the full set of memory states $|0>_{\mathcal{N}}$, for all $\mathcal{N}$.

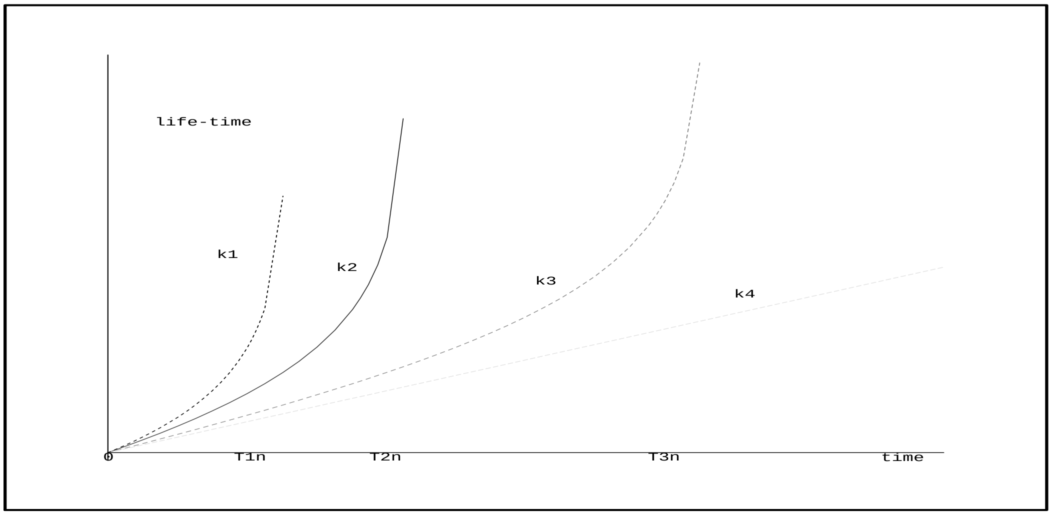
The brain is thus described as a complex system with a huge number of macroscopic quantum states (the memory states). The dissipative dynamics introduces $\mathcal{N}$-coded "replicas" of the system and information printing can be performed in each replica without reciprocal destructive interference. A huge memory capacity is thus achieved [17].

3 The parametric extension of the dissipative model

In the parametric dissipative model the dwq frequency is assumed to be time-dependent [20]. Remarkably, it is found that in such a case the couple of equations describing the dwq A and the "doubled" modes $\tilde{A}$ is equivalent to the spherical Bessel equation of order n (n integer or zero) [20].

The coupled system $A - \tilde{A}$ is then found to be described by a parametric oscillator of frequency $\Omega_n(k, t)$. The time-dependence of this frequency means that energy is not conserved in time and therefore that the $A - \tilde{A}$ system does not constitute a "closed" system. However, when $n \to \infty$, Ω_n approaches to a constant, i.e. energy is conserved and the $A - \tilde{A}$ system gets "closed" in such a limit. Thus, as $n \to \infty$ the possibilities of the system A to couple to $\tilde{A}$ (the environment) are "saturated": the system A gets *fully* coupled to $\tilde{A}$. This suggests that n represents the number of *links* between A and $\tilde{A}$. When n is not very large (infinity), the system A (the brain) has not fulfilled its capability to establish links with the external world. We also have that n "graduates"

Figure 1: “Lives” of k modes, for fixed n



the rate of variations in time of the frequency, i.e. the ”rapidity” of the system response to external stimuli.

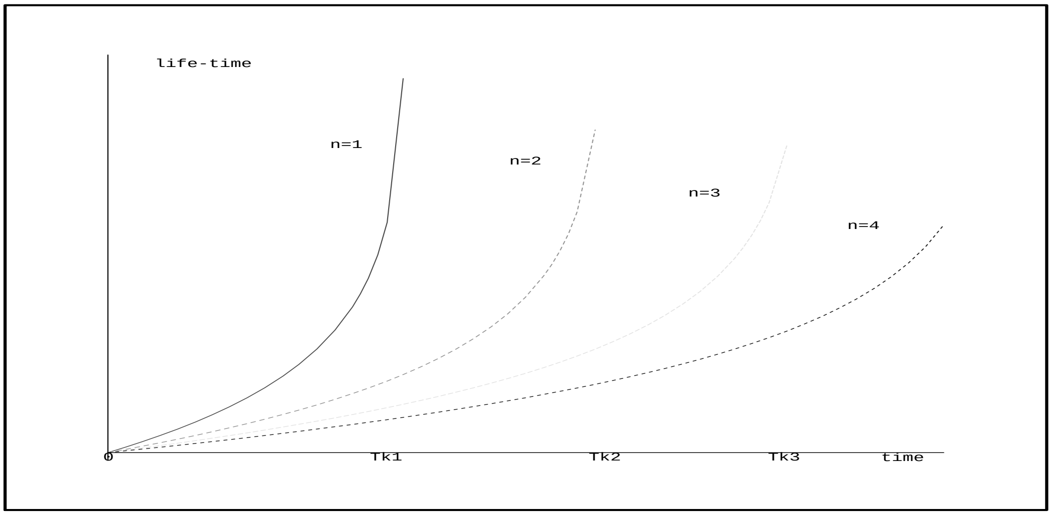
In order that memory recording may occur, $\Omega_n(k,t)$ has to be real. Such a condition is satisfied only in a limited span of time $T_{k,n}$. For fixed k, $T_{k,n}$ grows linearly in n, which means that the time span useful for memory recording (the ability of memory storing) grows as the number of links with the external world grows: more the system is ”open” to the external world (more are the links), better it can memorize (high ability of learning).

The reality condition also implies that only modes with k greater or equal to a threshold $\tilde{k}(n,t)$ can be recorded. Such a kind of ”sensibility” to external stimuli also depends on some characteristic parameter L of the system.

This intrinsic infrared cut-off in turn implies that only wave-lengths $\lambda \leq \tilde{\lambda} \propto \frac{1}{\tilde{k}(n,t)}$ are allowed: thus (coherent) domains of sizes less or equal to $\tilde{\lambda}$ are involved in the memory recording. Such a cut-off shrinks in time for a given n. On the other hand, a growth of n opposes to such a shrinking. These cut-off changes correspondingly reflect on the memory domain sizes. It is thus expected that, for given n, ”more impressive” is the external stimulus, i.e. greater is the number of high k momentum excitations produced in the brain, more ”focused” is the ”locus” of the memory.

The finiteness of the size of the domains implies that transitions through different vacuum states at given t become possible. As a consequence, both the phenomena of association of memories and of

Figure 2: "Lives" of k modes, for growing n and fixed k



confusion of memories, which would be avoided in the regime of strict unitary inequivalence among vacua (i.e. in the infinitely long wave-length regime), are possible [17].

We also find that modes with larger k have a "longer" life with reference to time t. Only modes satisfying the reality condition are present at certain time t, being the other ones decayed (Fig. 1 and 2). This introduces an hierarchical organization of memories depending on their life-time: memories with a specific spectrum of k mode components may coexist, some of them "dying" before, some other ones persisting longer. The sizes of the associated memory domains are correspondingly larger or smaller.

4 Conclusions

The results presented above appear to fit qualitatively well with the physiological observations [22] that more the brain relates to external environment, more neuronal connections will form. We are referring to functional or effective connectivity, as opposed to the structural or anatomical one. While the last one can be described as quasi-stationary, the former one is highly dynamic with modulation time-scales in the range of hundreds of milliseconds [22]. These functional connections may quickly change and new configurations of connections may be formed extending over a domain including a larger or a smaller number of neurons. Such a picture finds a possible description in our

model, where the coherent domain formation, size and life-time depend on the number of links that the brain sets with its environment and on internal parameters.

The finiteness of the domain size implies a non-zero effective mass of the dwq. These therefore propagate with a greater "inertia" than in the case of infinite volume where they are massless. The domain correlations are consequently established with a certain time-delay. This appears to agree with the physiological observation that the recruitment of neurons in a correlated assembly is achieved with a certain delay after the external stimulus action [23, 22]. The dwq effective non-zero mass also acts as a threshold in the excitation energy of dwq so that, in order to trigger the recall process an energy supply equal or greater than such a threshold is required. When the energy supply is lower than threshold a "difficulty in recalling" may be experienced. At the same time, however, the threshold may positively act as a "protection" against unwanted perturbations (including thermalization) and cooperate to the stability of the memory state. In the case of zero threshold (infinite size domain) any replication signal could excite the recalling and the brain would fall in a state of "continuous flow of memories" [17].

Finally, note that *after* information has been recorded, memory stability implies that the brain cannot be brought to the state in which it was *before* the information printing occurred (*Now*, you know it!...). Thus, the same fact of getting information introduces a partition in the time evolution, it introduces the *distinction* between the past and the future, a distinction which did not exist *before* the information recording (the psychological *the arrow of time*).

In fact, the main feature of dissipative quantization is that at each time t the system ground state $|0(t) >$ is labeled by t ("foliation"), so that at $t' \neq t$ the ground state $|0(t') >$ is unitary inequivalent to $|0(t) >$: in its time evolution the system runs over unitarily inequivalent representations. Such a non-unitary time evolution is found to be controlled by the entropy variation rate, as expected since dissipation implies irreversibility [21]. The psychological *arrow of time* thus naturally emerges in the dissipative quantum model. Moreover, the system ground state is found to be a thermal state [10, 21, 17], and the psychological arrow of time is actually concord [20] with the thermodynamical arrow of time and with the cosmological arrow of time (defined by the expanding Universe direction) [24, 25].

References

[1] E. Schrödinger, *What is life?*, Cambridge University Press, Cambridge 1967

[2] L.M.Ricciardi and H.Umezawa, *Kibernetik* **4**, 44 (1967)

[3] C.I.J.Stuart, Y.Takahashi and H.Umezawa, *J. Theor. Biol.* **71**, 605 (1978)

[4] C.I.J.Stuart, Y.Takahashi and H. Umezawa, *Found. Phys.* **9**, 301 (1979)

[5] S. Sivakami and V. Srinivasan, *J. Theor. Biol.* **102**, 287 (1983)

[6] H. Fröhlich, *J.Quantum Chemistry* **2**, 641 (1968); In H.Frhlich (Ed.), *Biological coherence and response to external stimuli*,p.1, Springer-Verlag, Berlin 1988

[7] E.Del Giudice, S.Doglia, M.Milani and G.Vitiello, *Nucl. Phys.* **B251 [FS 13]**, 375 (1985); *Nucl. Phys.* **B275 [FS 17]**, 185 (1986)

[8] E.Del Giudice, G. Preparata and G. Vitiello, *Phys. Rev. Lett.* **61**, 1085 (1988)

[9] P.W. Anderson, *Basic notions of condensed matter physics*, Benjamin, Menlo Park 1984

[10] H.Umezawa, *Advanced field theory: micro, macro and thermal concepts*, American Institute of Physics, N.Y., 1993

[11] K.H.Pribram, *Brain and perception*, Lawrence Erlbaum, New Jersey, 1991

[12] K.H.Pribram, *Languages of the brain*, Englewood Cliffs, New Jersey, 1971

[13] W.J.Freeman, *Intern. J. of Neural Systems* **7**, 473 (1996)

[14] W.J.Freeman, *Neurodynamics: An exploration of mesoscopic brain dynamics*, Springer, N.Y., 2000

[15] H.Umezawa, *Math. Japonica* **41**, 109 (1995)

[16] M. Jibu and K. Yasue, *Quantum brain dynamics and consciousness*, J. Benjamin, Amsterdam 1995

[17] G. Vitiello, *Int. J. Mod. Phys.* **9**, 973 (1995)

[18] M.Jibu , K.H.Pribram and K.Yasue, *Int. J. Mod. Phys.* **B10**, 1735 (1996)

[19] E.Pessa and G.Vitiello, *Biolectrochemistry and bioenergetics* **48**, 339 (1999)

[20] E.Alfinito, G. Vitiello, *Formation and Life-time of memory domains in the dissipative quantum model* in press on *Int. J. Mod. Phys.B*, quant-ph/0002014

[21] E. Celeghini, M. Rasetti and G. Vitiello, *Annals of Phys. (N.Y.)* **215**, 156 (1992)

[22] S.A.Greenfield, *Communication and Cognition* **30**, 285 (1997)

[23] B.Libet, E.W.Wright, B.Feinstein and D.K.Pearl, *Brain* **102**, 193 (1979)

[24] E.Alfinito, R.Mańka and G.Vitiello, *Class.Quant.Grav* **17**, 93 (2000)

[25] S.W.Hawking, *Phys. Rev.* **D32**, 2389 (1985)